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Longitudinal inequalities in Sq current system along 20^0 - 210^0 E meridian

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ABSTRACT
In the present study, longitudinal inequalities in Sq current system have been examined utilizing the data of northern and southern hemispheric stations for the period 1976 - 1977 along 20^0-210^0 E meridian. The anomalous behavior in the horizontal component (H) at a few southern hemispheric stations reveal that the solar quiet daily (Sq) variations in longitudinal sector (20°-120° E) do not show the expected V type or inverted V shaped variations but instead are marked by northern hemispheric D variations.

The technique of Principal Component Analysis (PCA) is applied to the D, H and Z components of the Earth's magnetic field. First Principal Component (PC-1) brings out a well defined anticlockwise loop with focus near geomagnetic latitude (~ 26.0° N) at 11 hours local time in the northern hemisphere and clockwise with focus near geomagnetic latitude (~ 43.2° S) at 12 hours local time in the southern hemisphere. This phenomenon has been observed during summer months and disappearance of the northern and southern hemispheric 'Sq-Vortex' during winter months. Anomalous deformation of Sq vortex, confined to longitudinal sector (20° to 120° E) may arise due to the changes in the local ionospheric conductivity and tidal winds driven by the main geomagnetic field.

Key words: D, H and Z components of Earth's magnetic field, Principle component analysis, Sq current system, Sq vortex deformation

INTRODUCTION

The daily variations in the Earth's magnetic field components recorded on Magnetograms during magnetically quiet days are known as solar quiet (Sq) daily variations (Matsushita and Campbell, 1967). Schuster (1889) was first to suggest that the current system responsible for producing the geomagnetic daily variations which is primarily of external origin and is associated with the currents flowing in the Earth's atmosphere. These currents are generated by the gases present in the ionosphere which are ionized by X-rays and extreme ultra violet rays from the Sun (Schuster, 1889, 1908). The dynamo currents flowing in the E-region of the ionosphere due to atmospheric tidal motion across the geomagnetic field causes Sq variations (Matsushita and Campbell, 1967; Padatella et al., 2011). The current system associated with the geomagnetic daily variation is typically termed the solar quiet (Sq) current system. These Sq current system is flowing at ~ 110 km altitude in the thin ionospheric E-layer and has two large horizontal current vortices (with Sq focus ~ 35^0 geographic latitude north and south) on either side of the magnetic equator, flowing anti-clockwise in the northern hemisphere and clockwise in the southern hemisphere (Richmond et al., 1976; Rastogi 1993; Takeda 2002; Yamazaki and Yumoto, 2012).

This Sq current system which surrounds the Earth, is relatively fixed in position with respect to the Sun. As the Earth rotates under this overhead daytime current system, the observatories along a longitude line rotate through 360° in 24 hours, experiencing daily variations. If one compares the quiet day Magnetograms from two observatories at the same latitude but different longitudes, they are found to be very similar but the phase of the curves is different by an angle equivalent to the time difference between the observatories. The strength of the S_q current system as well as the position of the S_q focuses change appreciably from day to day, season to season, solar activity or with the latitudes and longitudes (e.g., Patil et al., 1985; Bhardwaj and Rangarajan, 1998; Le Sager and Huang, 2002; Takeda, 2002; Stening et al., 2007; Torta et al., 2010; Pedatella et al., 2011; Pham Thi Thu et al., 2011; Shinbori et al., 2014).The other factors affecting the Sq current system are (a) tidal winds (Takeda, 2013), (b) ionospheric conductivity (Takeda et al.,1986) and (c) changes in orientation of Earth's geomagnetic main field (Cnossen and Richmond, 2013).

Generally, it is thought that Sq represents the real solar quiet daily variations but these variations include other disturbances from magnetospheric currents, storm time variations, pulsations and irregular disturbances that vary with a period of solar day (Xu and Kamide, 2004). In general, their contributions cannot be completely removed and are included in the obtained Sq field calculated from 5 IQ days. These disturbances are reflected as abnormal variations in Sq field termed as AQD's and are discussed by Bhardwaj et al., (2015) for Indian sector.

In the present study, data sets of 1976 and 1977 have been utilized. Earlier these data sets were analyzed by Campbell et al., (1993) along Indo-Russian chain of stations

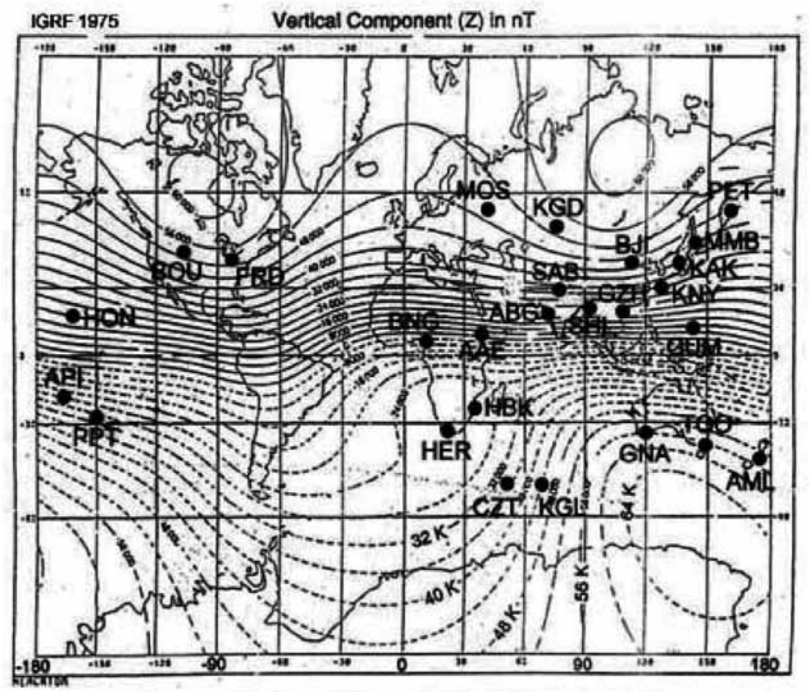

Figure 1. Locations of northern and southern hemispheric geomagnetic observatories at different latitudes and longitudes are shown against the iso-magnetic map of main field vertical component.

by using spherical harmonic analysis technique to separate the internal and external contribution of Sq field variations and reported that Sq vortex disappeared during the winter months for both the years. Rastogi (1993) had brought out changes in the summer-winter variation pattern in the eastward field based on magnetic field component data for the period 1975-76. Similar results were obtained by Alex and Jadhav (2007) by analyzing D and H variations for low solar activity period 1977. In the above studies, data sets from Indo-Russian chain (75^0 E longitude) are considered, whereas in the present study, data sets from northern and southern hemispheric observatories along 20^0-280^0 E longitude have been analyzed for longitudinal as well as seasonal variations of ionospheric Sq current system.

Data and Technique used

The data used in this analysis are the hourly values of the East-West (D), North-South (H) and Vertical (Z) components of the Earth's magnetic field for 5-International Quiet (IQ) days as suggested by Chapman and Bartels (1940) for the years 1976 and 1977 (a low solar activity period). We have combined 5 IQ days of each month to calculate monthly mean for every month for both the years 1976-77. The data were also corrected for non-cyclic variation (Matsushita and Campbell, 1967) and interpolated to local time (LT) for all the three components D, H and Z. To see the longitudinal as well as seasonal dependence of solar quiet day variations globally, data from seventeen northern and nine southern hemispheric observatories were analyzed. These stations are superimposed on the iso-magnetic 1975 epoch (IAGA working group, 1975) map of main field vertical component (Z) as shown in Figure 1 and details are shown in Tables 1 and 2.

The technique of Principal Component Analysis (PCA) is applied to monthly mean data to see the seasonal as well as longitudinal variations in the Sq current system. This is a well known technique applied for separating the normal and the abnormal geomagnetic field variations (Vertlib and Wagner, 1970; Faynberg, 1975). Gurubaran (2002) applied this method to the ground geomagnetic data in the Central Asian sector (72° – 83° E) to study about the equatorial counter electrojet (CEJ). Bhattacharyya and Okpala (2015) have applied this technique to extract information about equatorial electrojet (EEJ) for Indian observatories Tirunelveli (TIR) and Alibag (ABG). Xu and Kamide, (2004) have used the above method for decomposing the daily magnetic variations in Sq and S_D. Abnormal Sq variations were determined by Alex et al., (1998) and Bhardwaj et al., (2015). In spherical harmonic analysis (SHA), it is difficult to approximate sharp changes in latitude such as electrojet or local strong anomaly, even if high order spherical functions are used (Matsushita and Maeda, 1965). In the present work, we applied PCA technique to observe seasonal and longitudinal variations in both the hemispheres. Only normal variations reflected in PC-1 are considered and abnormal variations reflected in PC-2 do not show significant variations.

Table 1. Geographic and Geomagnetic coordinates of Northern hemispheric stations with their IAGA code

Observatory Name	IAGA Code	Geographic		Geomagnetic	
		Latitude (°N)	Longitude (°E)	Latitude (°N)	Longitude (°E)
Moscow	MOS	55.73	37.63	50.79	121.62
Fredericksburg	FRD	38.12	282.38	49.60	349.80
Boulder	BOU	40.08	254.46	49.00	316.50
Petropavlovsk	PET	53.06	158.38	44.40	218.20
Karaganda	KGD	49.82	73.08	40.56	150.04
Memambetsu	MMB	43.55	144.12	34.00	208.40
Beijing	BJI	40.06	116.18	29.12	186.20
Kakioka	KAK	36.14	140.11	26.00	206.00
Honolulu	HON	21.19	202.00	21.10	266.50
Sabhawala	SAB	30.33	77.80	20.78	151.34
Kanoya	KNY	31.25	130.53	20.50	198.10
Shillong	SHL	25.57	91.88	15.10	163.70
Guangzhou	GZH	23.09	113.34	12.10	-176.01
Alibag	ABG	18.63	72.87	9.64	145.39
Addis Ababa	AAE	9.02	38.46	5.30	109.20
Bangui	BNG	4.26	18.34	4.60	88.5
Guam	GUM	13.35	144.52	4.00	212.9

Table 2. Geographic and Geomagnetic coordinates of southern hemispheric stations with their IAGA code

Observatory Name	IAGA Code	Geographic		Geomagnetic	
		Latitude (°S)	Longitude (°E)	Latitude (°S)	Longitude (°E)
Hermanus	HER	34.42	19.23	33.7	81.7
Hartebeesthoek	HBK	25.88	27.68	27.0	92.1
Crozet	CZT	46.43	51.87	51.4	190.7
Kerguelen	KGL	49.35	70.20	56.5	127.8
Gnangara	GNA	31.78	115.95	43.2	185.8
Toolangi	TOO	37.53	145.47	46.7	220.8
Amberley	AML	43.15	172.72	47.7	252.5
Apia	API	13.80	188.23	16.0	260.2
Papeete-Pamatai	PPT	17.57	210.42	15.3	282.8

RESULTS AND DISCUSSION

Characteristics of Sq in Southern and Northern Hemispheres

Comparison between southern and northern hemisphere diurnal variations is shown in Figure 2. Figure 2 (a-f) shows the monthly mean diurnal variations in H, D and Z components for four southern hemispheric stations: Crozet (CZT), Kerguelen (KGL), Gnangara (GNA) and Hermanus (HER) and two northern hemispheric stations Memambetsu (MMB) and Moscow (MOS). For southern hemispheric stations Crozet (CZT), Kerguelen (KGL), Gnangara (GNA) and Hermanus (HER), the North-South component (H) shows positive variations in the forenoon and negative variations in the afternoon (i.e. easterly maxima in the forenoon hours and westerly minima in the afternoon hours). Note that the amplitude of H-variations decreases as one approaches Sq focus. Also the East-West component (D) shows a negative variation in the morning followed by a positive one in the afternoon (i.e. westerly minima in the forenoon hours and easterly maxima in the afternoon hours). Z-component shows the expected southern hemispheric type of variations. The declination D, positive eastward, and the horizontal component H, positive northward, have been considered as the vertical

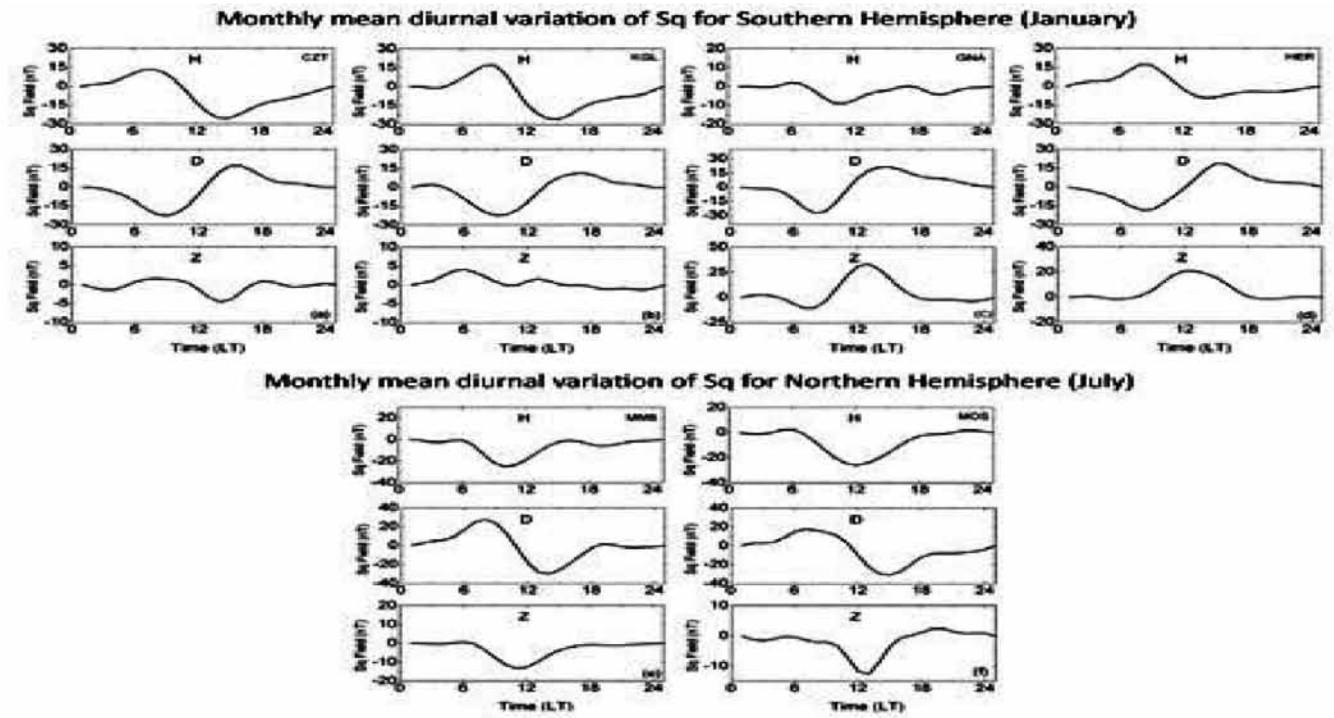

Figure 2. Monthly mean diurnal variations of Sq in Southern (a) Crozet (b) Kergulen (c) Gangara (d) Hermanus and Northern (e) Memabetus (f) Moscow hemispheric stations.

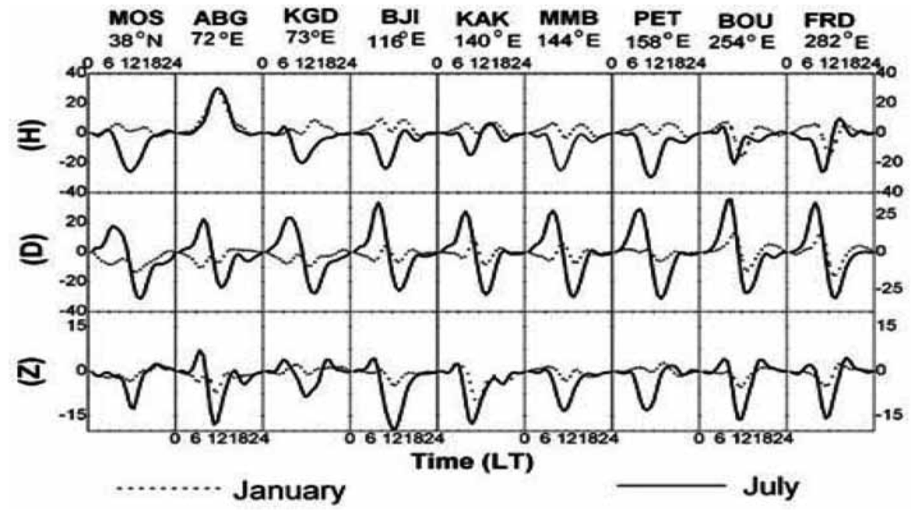

Figure 3. Plots of monthly mean diurnal variation of Sq for summer (July) and winter (January) months at Northern hemispheric stations.

component Z does not feature a strong longitudinal dependence (Le sagar and Huang, 2002).

Figure 3 shows the monthly mean diurnal variations of Sq in H, D and Z components at 9 northern hemispheric stations for summer (solid line) and winter (dashed) months at different latitudes and longitudes showing expected northern hemispheric type of variations. The North-South component (H) shows inverted V-type of variations for equator-ward stations like Alibag (ABG) and V-shaped variations for other stations situated towards pole-ward side of the Sq focus. The waveform is about to reverse its sign from V- type to inverted V- shape between mid-latitude stations Kakioka (KAK) and Beijing (BJI) and stations above these latitudes are characterized by V-shaped variations with minimum around local noon. The East-West component (D) exhibit expected easterly maximum in forenoon hours and minimum in early afternoon hours. In their latitudinal progression, D-variations are

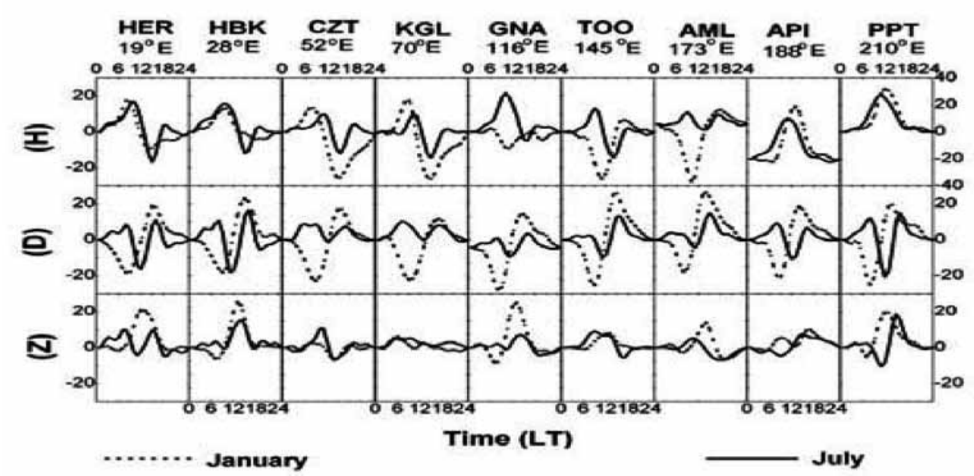

Figure 4. Plots of monthly mean diurnal variation of Sq for summer (January) and winter (July) months at Southern hemispheric stations.

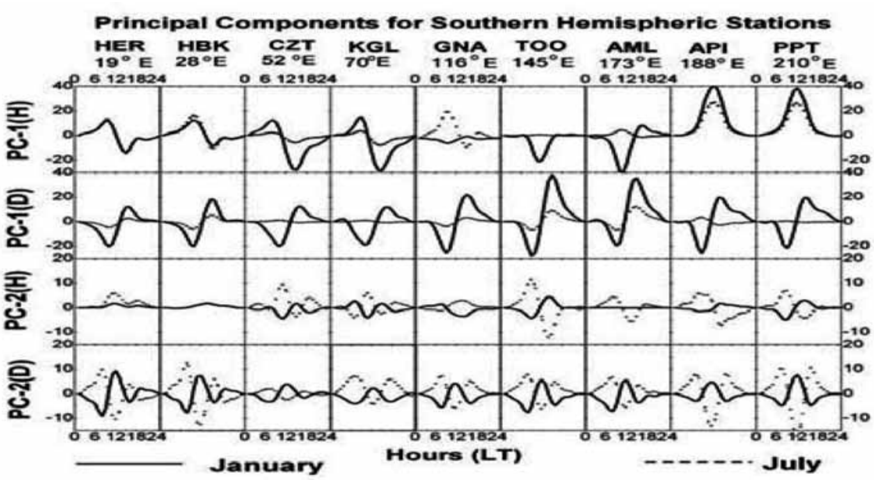

Figure 5. First and second principal components of H and D for Southern hemispheric stations at different longitudes for two representative months describing summer (January) and winter (July) seasons.

strongest at mid-latitudes (KAK & BJI). The D-maximum at KAK and BJI coupled with reversal of H variation near these latitudes clearly indicate that focus of the northern Sq vortex during summer month is located between the latitudes of KAK and BJI.

Figure 4 is similar to Figure 3 but for southern hemispheric stations. In this figure, the North-South component (H) shows northern hemispheric type D – variations at few stations. At Apia (API) and Papeete-Pamatai (PPT) it shows expected inverted V- type variations, which indicates that these stations are situated towards the equator side of the Sq focus, whereas at Toolangi (TOO) and Amberley (AML) it shows expected V- type of variations as these stations are located towards pole-ward side of the Sq focus. The D and Z components however, show as expected, southern hemispheric type of variations. The D-maximum at GNA coupled with H minimum clearly denotes that the focus of the southern Sq vortex during summer month is located near GNA. D waveform has opposite nature between summer and winter months at all southern hemispheric stations HER, HBK, CZT, KGL, GNA, TOO, AML, API and PPT. The D-variation between 06:00 and 12:00 h LT (Figure 4) is negative in January and positive in July at all stations. This supports the existence of IHFACs in the dawn and the noon sectors (Yamashita and Iyemori, 2002) where these currents are flowing from northern to southern hemisphere during dawn and southern to northern hemisphere during noon and dusk sectors during summer months.

Figure 5 shows the plot of first and second principal components in H and D for summer (January) and winter (July) time at nine southern hemispheric stations. These stations are located between geographic longitudes 19^0-210^0 E. The D-variations, with morning minimum and early afternoon maximum are typical characteristics of southern hemispheric stations. This waveform is well developed

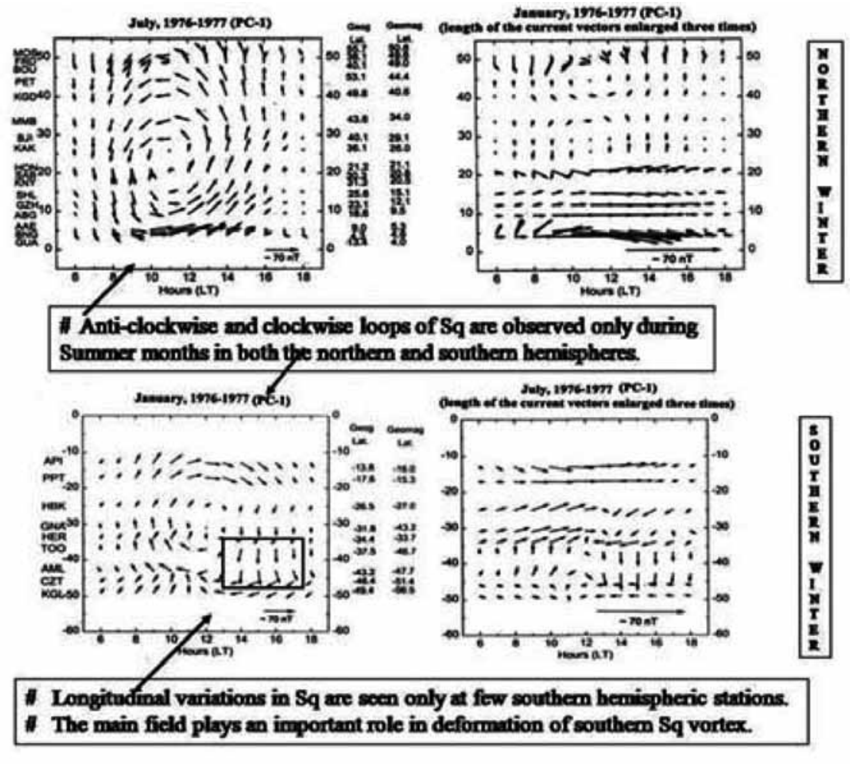

Figure 6. Plots of equivalent current vectors on the local time-latitude sector for first principal component in the Northern (upper panel) and Southern (lower panel) hemispheres during summer and winter months.

in summer time (January) but almost vanishes during winter (July). H-variations at API and PPT are dominated by noontime maximum, whereas variations at TOO and AML, particularly for January month, are marked by noon-minimum. Both these "Inverted-V" type and "V-shaped" variations are typical of stations located on the equator-ward and pole-ward side of the Sq focus. However, the H variations at southern hemispheric stations (HER, HBK, CZT, KGL and GNA) in the longitudinal band of 20°-120° E do not show expected "V or inverted-V" type of pattern. Instead diurnal plots are dominated by forenoon maximum and afternoon minimum (i.e., eastward magnetic field due to southward current in the forenoon and westward directed magnetic field due to northward current in the afternoon hours) and shows northern hemispheric type D-variations. This anomalous behavior is quite conspicuous in summer (January) but also observed in winter (July) and is in agreement with the observations made by Le Sagar and Huang (2002) for American sector.

In Figure 5 the PC-2 (H) curves for summer (January) month show reverse variations with that of winter (July) month. For summer month (solid curves) a small decrease in the field in the forenoon hours, which is increased in the afternoon hours, could be noticed at low latitude stations TOO, API and PPT, the waveform reverses at CZT and KGL and almost vanishes at mid latitude stations HER and HBK. During winter months (dashed curves) a positive excursion in the forenoon hours and negative in the afternoon hours can be seen almost at low and mid latitude stations. The PC-2 (D) curves for winter month (dashed curves) show two peaks one in the morning and other in the after-noon hours with maximum variation at HER, HBK, API and PPT which is decreasing in amplitude at other stations. The summer curves (solid one) for PC-2(D), shows reverse variation with that of July. A minimum in the morning hours and the second minimum in the afternoon hours have been observed at latitudes in the southern hemisphere.

The causes of disappearance of Sq current system during winter months in both the northern and southern hemispheres are as: PCA of Sq (D) variations indicates the presence of two distinct patterns, one corresponding to regular Sq and the other associated with second component which has different waveform both in northern and southern hemispheres. The second component, indicative of the presence of strong inter-hemispheric currents, undergoes much strong seasonal variability than the first component (Figure 5). It is deduced that the magnetic effects associated with these currents tend to dominate the weak wintertime Sq dynamo effects, accounting for the disappearance of Sq vortex in both northern and southern hemispheres during winter months. Similar results have been reported by Campbell et al., (1993) and Rastogi (1993) for the Indian region. Chulliat et al., (2005) suggest that the seasonal asymmetry in the geomagnetic 12 h and 24 h variations at mid latitudes is a global phenomenon, due to a corresponding seasonal asymmetry in the lower thermospheric winds responsible for these variations through the ionospheric dynamo.

Longitudinal inequalities in Sq vortex

Northern Hemisphere

Figure 6 shows the equivalent current vector plots for the first principal component during summer and winter months for both northern (upper panel) and southern (lower panel) hemispheres. Here, the hourly values of H and D components are combined to produce the magnetic vector. The resulting magnetic vector when rotated clockwise by 90° gives the equivalent current vector. When placed on the latitude-local time cross-section, it helps to trace nature of equivalent Sq current system. The July plot in upper panel of Figure 6 clearly shows that flow path is dominated by an anti-clockwise Sq vortex with well-marked focus near Kakioka (KAK) (~ 26.0° N geomagnetic latitude) and around 11 hours local time in the northern hemisphere. The magnitude of the current vectors for January month is enlarged three times, to see the direction of the current whorl clearly. Here in this figure no signature of current loop can be seen for the first principal component during northern winter month.

Southern Hemisphere

The bottom panel of Figure 6 shows the equivalent current vector plots for southern summer (January month) and winter (July month) for the first principal component. Here, in this figure (lower left portion) although a clockwise Sq loop with focus near Gnangara (GNA) (~ 43.2° S geomagnetic latitude) at 12 hours local time can be traced for January month, the nature of vector pattern is much less regular than that seen in the northern hemisphere during summer month. As suggested by Price and Wilkins (1963), Matsushita and Maeda (1965) and Sugiura and Hagan (1967), from the analysis of world wide data that the intensity of current vortices was larger at northern hemisphere than southern hemisphere, and foci of the main current vortices appeared later in time and at high latitude in southern hemisphere. Thus, we observe Sq focus at GNA. No sign of vortex can be seen during July (winter month) in the southern hemisphere for the first principal component.

In Figure 6 (lower left portion) during summer (January), current vectors at certain stations deviate significantly from those expected from regular oval shaped Sq vortex. Most significant perturbations are seen at TOO & AML. The current vectors at these stations in the afternoon hours are directed southward, as against the expected SW orientation as shown in inset. But the current vectors at these stations in pre-noon sector show an expected NW orientation. The current vectors at HER, CZT and KGL (location in Southern part of Indian Ocean) in the morning hours deviate from expected NW direction to NE direction. But again at these stations the current vectors in afternoon hours have expected SW directions. These changing vector directions between forenoon and afternoon at selected stations are indicative of the longitudinal variations in southern-hemispheric Sq-current system.

To study about the longitudinal inequalities, three different regions in southern hemisphere are considered with respect to geomagnetic longitude: zone-1- Australian sector, zone-2 -Indian Ocean and zone 3 - African sector. The nature of Sq vortex over Australian, Indian Ocean and African sectors is shown in Figure 7. The southern Sq vortex over the Australian sector appears to have normal oval shape but as it shifts its central position to Indian Ocean, pole-ward side of the vortex undergoes significant deformation.

In the afternoon sector, the vortex tends to be stretched in N-S direction to produce N-S oriented current vectors at TOO and AML. In the morning sector, the current iso-lines deviate from North-West orientation to North-East orientation, to produce anomalous current vector pattern at HER, CZT and KGL. The normal behavior of current vectors at HER, CZT and KGL in the afternoon hours (expected SW orientations) suggest that deformed current vortex returns to normal oval shape as the central meridian of vortex transit from Indian Ocean sector to the western part of Africa.

DISCUSSION

Ionospheric conductivity and tidal winds play an important role in the shape and strength of the Sq current system (Richmond et al., 1976; Takeda, 2013). Thus, the seasonal and longitudinal differences in Sq current system may be related to variations in conductivity or tidal winds or combination of the two. Since the conductivity depends upon the geomagnetic main field strength, longitudinal variations in this field strength may introduce longitudinal differences in the Sq current system (Matsushita, 1967). Modeling results have suggested that the conductivities associated with geomagnetic field variations can induce longitudinal variations in field aligned currents that are related to longitudinal differences in the hemispheric asymmetry of the Sq current system (Stening et al., 2007). In Figure 5, first principal component (PC-1) along the longitudinal band of 20°-120° E, denotes the anomalous behavior in H component at stations HER, HBK, CZT, KGL and GNA as they do not show expected "V or inverted-V" type of pattern but show northern hemispheric type D-variations for summer (January) month. This indicates

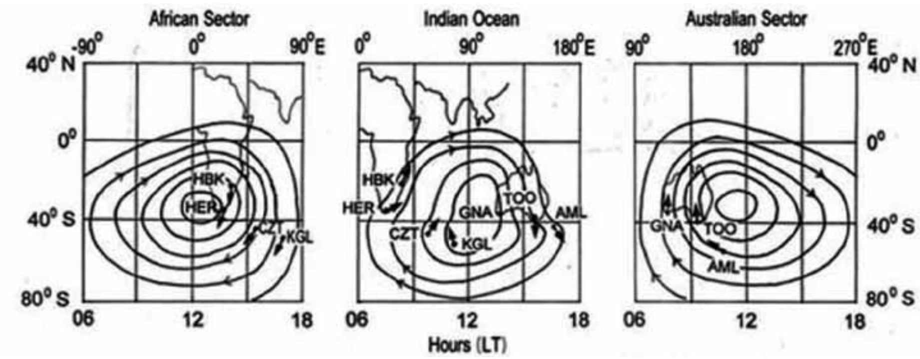

Figure 7. Longitudinal inequalities in the southern hemispheric Sq current vortex as it moves from the Australian sector to African sector through the Indian Ocean (After Matsushita, 1965).

that the currents are flowing in the north-south direction as observed in Figure 6 (lower LHS panel). As shown in Figure 1, these stations are located in the region of strong magnetic field strength. Enhancement of geomagnetic field denotes reduction in the ionospheric conductivity and hence in the ionospheric current system in this region. However, the influence of reduced conductivities related to enhanced geomagnetic field strength should be minimal due to the fact that the dynamo generated currents are proportional to $u \times B$, where u is the neutral wind velocity and B is the main geomagnetic field (Richmond, 1989; Takeda, 1996). Thus, the geomagnetic main field strength may contribute significantly to the longitudinal variations in Sq current system.

Using Spherical Harmonic Analysis method (SHA), Matsushita (1965) also reported the longitudinal and hemispheric inequalities of the external Sq current systems in three longitudinal zones and their world-wide average for equinoxes during the IGY period. He suggested, because of the anomaly of the geomagnetic main field, the dip latitude is distorted with respect to the geographic latitude, particularly in the southern hemisphere. This distortion causes great deformation of current vortices in the South African and American zones and concluded that the main causes of the hemispherical inequality and longitudinal inequality is due to the differences of ionospheric wind pattern with respect to the geomagnetic main field.

The other possibility is the tidal wind system that drives the ionospheric wind dynamo. Tidal winds are described with respect to geographical coordinates while ionospheric electric fields and currents are arranged with respect to magnetic coordinates. This offset between the geographic and geomagnetic equators may introduce longitudinal variation in the Sq current system. According to Pedatella et al., (2011), longitudinal structure in the Sq current is partly driven by the geomagnetic field and seasonal variation of the longitudinal structure may be related to the seasonal variation of the tidal winds and the offset between the geomagnetic and geographic equators. Observation and modeling results have also demonstrated that the non-migrating tides will also play an important role in producing longitudinal Sq variations in the equatorial fields, ionospheric densities and thermospheric winds (England et al., 2006; Häusler et al., 2010; Pedatella et al., 2011; Chandrasekhar et al., 2014).

Thus the anomalous vectors observed between the longitudinal belt (20^0-120^0 E) could be related to the tidal winds partly driven by geomagnetic main field. Our observations are based on limited stations and to understand the physical mechanism of scattering of Sq current vectors in southern hemisphere, we need to carryout numerical modeling that will help in understanding the physical mechanism of the observed Sq current vectors.

CONCLUSIONS

- The anti-clockwise and clockwise loops of ionospheric Sq current system in the northern and southern hemispheres are observed only during summer and disappear completely during winter months for the first principal component which shows seasonal variations in Sq current system.
- In the present study (20^0-210^0E), longitudinal variations in Sq current system are observed at a few southern hemispheric stations between 20^0 – 120^0 E. The deformation in the southern hemispheric Sq vortex could be related to local ionospheric conductivity anomaly along with tidal winds driven by the main geomagnetic field.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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